

Effects of degenerate sterile neutrinos on the supernova neutrino flux

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Abstract

We consider the possibility that there exist sterile neutrinos which are closely degenerate in mass with the active neutrinos and mixed with them. We investigate the effects of this kind of active-sterile neutrino mixing on the composition of supernova neutrino flux at the Earth. If an adiabatic MSW-transition between active and sterile neutrinos takes place, it could dramatically diminish the electron neutrino flux.

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1 Introduction

Sterile neutrinos closely degenerate with active neutrinos may have, if they exist, escaped detection in the laboratory and astrophysical experiments performed so far. They can, however, reveal themselves through measurable oscillation effects in astronomical-scale baselines [1, 2]. They may affect the relative fluxes of the active neutrinos at the Earth if the mass-squared difference obey $\delta m^2 \gtrsim E/L$, where L is the distance to the source and E is the energy of neutrinos. With ultrahigh-energy cosmic ray (UHECR) neutrinos one can reach the sensitivity of $\delta m^2 \gtrsim 10^{-18} \text{ eV}^2$ in the future neutrino telescopes like the ICECUBE [3]. It should be emphasized that the mass-squared differences below $\delta m^2 \lesssim 10^{-11} \text{ eV}^2$ cannot be probed in solar neutrino, atmospheric neutrino or laboratory experiments. The most stringent present constraint on the active-sterile neutrino mixing comes from cosmology [4], $|\delta m^2| \sin^2 2\varphi < 5 \times 10^{-8} \text{ eV}^2$. (These cosmological bounds may be avoided in the case of large lepton number asymmetries in the early universe [5]). It is generally thought that neutrinos are produced in UHECR sources via a pion-muon decay chain, which yields the flux ratios $F_e^0 : F_\mu^0 : F_\tau^0 = 1 : 2 : 0$, where F_α^0 is the flux of the neutrino flavour ν_α . If one considers only the active neutrinos ν_e, ν_μ and ν_τ and takes into account their "bi-large" mixing behaviour, observed in the solar and atmospheric neutrino measurements, the flavour ratios of neutrinos at the Earth are predicted to be $F_e : F_\mu : F_\tau = 1 : 1 : 1$ [6]. In [1] we found that active-sterile mixings with a tiny δm^2 can change these ratios at the level of tens of percents. The effects of this size should be easily detected in the future experiments.

In the present paper we shall extend our analysis of the degenerate active-sterile mixing to supernova neutrinos. As far as oscillations are concerned, the situation is for supernova neutrinos quite different from that for the UHECR neutrinos. In the case of UHECR neutrinos, the vacuum oscillations play a central role while for the supernova neutrinos matter effects are decisive and vacuum oscillations have usually no effects. In the case of supernova neutrinos the energy is also much lower, so they could be studied with experiments like HyperK and UNO.

In the dense core of the supernova the neutrino Hamiltonian is extremely matter dominated. The interaction eigenstates, in which neutrinos are produced in various weak interaction processes in the core, coincide in a good accuracy with the eigenstates of this Hamiltonian. In transit through the envelope to the surface of the star, the flavour composition of these eigenstates changes. Neutrinos also pass through the MSW resonance regions corresponding to the solar and atmospheric oscillation scales, which may affect their behaviour. When leaving the star, neutrinos are in mass eigenstates that consist of different flavours according to the mixing

pattern they have in vacuum, and they will propagate as those states to the Earth without further oscillations. Consequently, if sterile neutrinos exist and if they mix with the active neutrinos, they will be present in the mass eigenstates entering the Earth. They will thereby affect the fluxes of the active neutrinos measured in neutrino detectors.

There is an interesting possibility that one or more of the degenerate active-sterile neutrino pairs encounter a resonant mixing in the outer skirts of the envelope of the star. This is possible if that pair has $|\delta m^2| \gtrsim 10^{-11} \text{eV}^2$, which corresponds to the oscillation length of the order of the giant progenitor star radius. Whether or not such a resonant mixing really occurs depends on how well the adiabaticity conditions are met in the resonance region, which in turn depends on the details of the density profile of the envelope in its outer skirts. If it does occur, it may change the flux ratios of neutrinos and antineutrinos dramatically, in particular if the active-sterile vacuum mixing angle is small.

2 A sterile mixing scenario

In the three-flavour framework the flavour fields ν_e, ν_μ, ν_τ and the mass eigenfields $\hat{\nu}_1, \hat{\nu}_2, \hat{\nu}_3$ are related to each other through $\nu_l = U_{li} \hat{\nu}_i$, where U is a mixing matrix, in the following parametrized as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}, \quad (1)$$

where $c_{jk} = \cos \theta_{jk}$ and $s_{jk} = \sin \theta_{jk}$ (we neglect the possible CP violation). The solar neutrino data, together with the recent KamLAND reactor data [7], indicate the mixing angle θ_{12} to be bounded into the range $0.50 < \theta_{12} < 0.67$ [8], [9]. On the other hand, observations of atmospheric neutrinos are consistent with maximal mixing between the mass eigenstates ν_2 and ν_3 , their mixing angle being within the range $0.64 < \theta_{23} < 0.96$ [9], [10]. The third mixing angle, θ_{13} , is bounded by the results of CHOOZ [11] and Palo Verde [12] to small values, $0 \leq \theta_{13} \leq 0.1$.

Let us now assume that there exists three sterile neutrinos ν_{s1}, ν_{s2} and ν_{s3} , which mix pairwise with the states $\hat{\nu}_1, \hat{\nu}_2$ and $\hat{\nu}_3$. We denote the new mass eigenstates that result from this mixing as follows ($i = 1, 2, 3$):

$$\begin{aligned} \nu_i &= \cos \varphi_i \hat{\nu}_i - \sin \varphi_i \nu_{si}, \\ \nu'_i &= \sin \varphi_i \hat{\nu}_i + \cos \varphi_i \nu_{si}. \end{aligned} \quad (2)$$

The antineutrino states are defined similarly. We assume that the mass difference of the states ν_i and ν'_i is so small that in the processes, like particle decays, which are measured in laboratory experiments, these two states are not distinguished but appear as a single state with couplings equal to those of the active state $\hat{\nu}_i$. There are models where degenerate neutrino pairs may naturally appear, see e.g. [13]. It should be emphasized that in some of these models like in the well-known Pseudo-Dirac model, the mixing angles are naturally close to their maximal value of $\frac{\pi}{4}$.

In the presence of the sterile neutrinos, the neutrino mixing matrix (1) is modified to the form

$$U^{(6)} = \begin{pmatrix} \cos \varphi_1 U_{e1} & \cos \varphi_2 U_{e2} & \cos \varphi_3 U_{e3} & \sin \varphi_1 U_{e1} & \sin \varphi_2 U_{e2} & \sin \varphi_3 U_{e3} \\ \cos \varphi_1 U_{\mu 1} & \cos \varphi_2 U_{\mu 2} & \cos \varphi_3 U_{\mu 3} & \sin \varphi_1 U_{\mu 1} & \sin \varphi_2 U_{\mu 2} & \sin \varphi_3 U_{\mu 3} \\ \cos \varphi_1 U_{\tau 1} & \cos \varphi_2 U_{\tau 2} & \cos \varphi_3 U_{\tau 3} & \sin \varphi_1 U_{\tau 1} & \sin \varphi_2 U_{\tau 2} & \sin \varphi_3 U_{\tau 3} \\ -\sin \varphi_1 & 0 & 0 & \cos \varphi_1 & 0 & 0 \\ 0 & -\sin \varphi_2 & 0 & 0 & \cos \varphi_2 & 0 \\ 0 & 0 & -\sin \varphi_3 & 0 & 0 & \cos \varphi_3 \end{pmatrix}. \quad (3)$$

Obviously, this is just one possible way to realise the mixing between three active and three sterile neutrinos, not the most general case.

3 Fluxes of supernova neutrinos

We shall now study the effects of the sterile neutrinos on the fluxes of supernova neutrinos. As mentioned, for supernova neutrinos matter effects play the main role, in contrast with the case of UHECR neutrinos, where vacuum oscillations are important. Because of the effects of matter, the flavour composition of the supernova neutrino flux observed at the Earth differs from that in the production region (see, e.g. [14, 15]).

The neutrinos and antineutrinos may undergo matter enhanced MSW transitions inside the star if $\delta m^2 \lesssim 10^4 \text{ eV}^2$. In the case of three active neutrinos there are two possible MSW-resonance regions, at the densities

$$\rho_H \sim 10^3 - 10^4 \text{ g/cm}^3, \quad \rho_L \sim 10 - 30 \text{ g/cm}^3. \quad (4)$$

The subscript H refers to the so-called high-resonance region, which corresponds to the atmospheric neutrino oscillation ($\delta m_{\text{atm}}^2 = 2.6 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{\text{atm}} = 0.52$ [9]), and the subscript L

refers to the low-resonance region, which corresponds to the large mixing angle (LMA) solar neutrino oscillations ($\delta m_{\odot}^2 = 6.9 \times 10^{-5} \text{ eV}^2$ and $\tan^2 \theta_{\odot} = 0.43$ [9]). In the case of the normal mass hierarchy ($m_1 \lesssim m_2 \ll m_3$) both resonances occur for neutrinos, whereas in the case of the inverse mass hierarchy ($m_3 \ll m_1 \lesssim m_2$) the high-resonance occurs for antineutrinos and low-resonance for neutrinos. If the system is not fully adiabatic, the MSW effect is not complete but a level crossing from one matter eigenstate to another will occur in the resonance region. The level crossing probability, the so-called Landau-Zener probability, is given in [16].

The matter effects depend on the density profile of the progenitor star. It can be shown (e.g. [15]) that propagation through the low-resonance region, determined by the solar neutrino parameters, is adiabatic, i.e. the Landau-Zener probability for it is $P_L = 0$. For the high-resonance one can distinguish three cases, defined by the values of $\sin^2 \theta_{13}$ and neutrino energy and differing in the values of the Landau-Zener probability (P_H) [15]:

1. Adiabaticity breaking region: $\sin^2 \theta_{13} \lesssim 10^{-6} \times (E/10 \text{ MeV})^{2/3}$, where $P_H \approx 1$;
2. Transition region: $\sin^2 \theta_{13} \sim (10^{-6} - 10^{-4}) \times (E/10 \text{ MeV})^{2/3}$, where $0 \lesssim P_H \lesssim 1$;
3. Adiabatic region: $\sin^2 \theta_{13} \gtrsim 10^{-4} \times (E/10 \text{ MeV})^{2/3}$, where $P_H \approx 0$.

In the adiabaticity breaking region the H-resonance has no effect to the evolution of the neutrino states, whereas in the adiabatic region a full conversion will occur. For simplicity, we will concentrate in what follows on these two extreme cases 1 and 3, omitting the transition region case 2.

In the standard case of three active neutrinos with the normal mass hierarchy the fluxes of the mass eigenstates leaving the star and entering the Earth later on, which we denote by $F = (F_1, F_2, F_3)$, are obtained from the production fluxes of the flavour eigenstate in the supernova core, denoted by $F^0 = (F_e^0, F_{\mu}^0, F_{\tau}^0)$, through [18]

$$F = P F^0, \quad (5)$$

where the matrix

$$P = \begin{pmatrix} P_H P_L & 1 - P_L & (1 - P_H) P_L \\ P_H (1 - P_L) & P_L & (1 - P_H) (1 - P_L) \\ (1 - P_H) & 0 & P_H \end{pmatrix}, \quad (6)$$

describes the conversion probability inside the star. The fluxes of different flavour eigenstate neutrinos ν_{α} at the Earth are then given by

$$F_{\alpha}^{SM} = \sum_{i=1}^3 |U_{\alpha i}|^2 F_i. \quad (7)$$

Let us now consider the situation in the case of three additional sterile neutrinos. Sterile neutrinos are not produced in the weak interaction processes taking place in the core of a supernova. Therefore, the fluxes of the mass eigenstates on the surface of the supernova are, like in the standard case, determined by the production rates of the active neutrinos in the core. Nevertheless, during the propagation of neutrinos through the envelope of the supernova, sterile components $\nu_{s1}, \nu_{s2}, \nu_{s3}$ are developed as a result of the active-sterile mixing, that is, active-to-sterile transitions take place. The flavour composition of the neutrino flux on the surface and at the Earth is given by

$$F_\alpha = \sum_{i=1}^6 |U_{\alpha i}^{(6)}|^2 F_i = \sum_{i=1}^3 \cos^2 \varphi_i |U_{\alpha i}|^2 F_i + \sum_{i'=1}^3 \sin^2 \varphi_{i'} |U_{\alpha i'}|^2 F_{i'} \quad (8)$$

where $\alpha = e, \mu, \tau, s1, s2, s3$ and F_i 's are given in Eq. (5) instead that P is now six-dimensional and $F^0 = (F_e^0, F_\mu^0, F_\tau^0, 0, 0, 0)$. If the active-sterile mixing angles φ_i are all equal, the relative fluxes of different flavours, F_α , do not differ from those of the standard case, F_α^{SM} . In particular, this is true in the case where all the mixing angles φ_i are close to their maximal value of $\frac{\pi}{4}$, as predicted by some models.

In the case of the normal mass hierarchy, antineutrinos do not encounter MSW resonant conversions, and they end up to different mass eigenstates than the corresponding neutrinos. The counterpart of the matrix P for antineutrinos is a unit matrix. Hence the active-sterile neutrino mixing affects antineutrinos and neutrinos differently, and consequently the ratio $F_\alpha/F_{\bar{\alpha}}$ generally differs from its value in the nonsterile case.

In the case of the inverted mass hierarchy, the high-resonance is encountered by antineutrinos and the low-resonance by neutrinos. Obviously, the fluxes of neutrino mass eigenstates on the surface of the star are obtained from Eq. (5) by setting $P_H = 1$. It is also straightforward to see that the antineutrino counterpart of the matrix P given in Eq. (6), denoted by \bar{P} , is obtained in the inverted mass hierarchy case from the matrix P by replacing P_H with \bar{P}_H (actually $P_H = \bar{P}_H$ [17]) and P_L with $1 - \bar{P}_L$ [18]. The fluxes of the active antineutrinos at the Earth are then given by

$$\bar{F}_\alpha = \sum_{i=1}^3 \cos^2 \varphi_i |U_{\alpha i}|^2 \bar{F}_i + \sum_{i'=1}^3 \sin^2 \varphi_{i'} |U_{\alpha i'}|^2 \bar{F}_{i'} \quad (9)$$

where $\bar{F}^0 = (\bar{F}_e^0, \bar{F}_\mu^0, \bar{F}_\tau^0, 0, 0, 0)$ are the fluxes of antineutrino flavours in the production region and \bar{F}_i 's on the right-hand side are obtained by

$$\bar{F} = \bar{P} \bar{F}^0. \quad (10)$$

Although the low-resonance point itself does not appear in the antineutrino sector, a conversion effect is possible at the low-density region, and \bar{P}_L takes into account the adiabaticity of this transition [14]. In our calculations we will assume $\bar{P}_L=0$.

4 Results

In the following we shall present numerical estimates for the flux ratios of supernova neutrinos at the Earth in the case of degenerate sterile neutrinos, and compare them with the corresponding results in the standard, nonsterile case. We allow the ordinary mixing angles θ_{ij} vary in their phenomenologically allowed regions quoted in Section 2. The active-sterile mixing angles φ_i are allowed to vary arbitrarily in the range from $\varphi_i = 0$ (no mixing) to $\varphi_i = \pi/4$ (maximal mixing).

There exists a considerable uncertainty concerning the initial fluxes of neutrino flavours in the production region in the core of the supernova. The value of the ratio $F_e^0 : F_{\bar{e}}^0 : F_x^0$, where $F_x^0 = F_\mu^0 = F_\nu^0 = F_\tau^0 = F_{\bar{\tau}}^0$, varies according to the model one uses [19]. Traditionally these fluxes are supposed to be equal, i.e. $F_e^0 : F_{\bar{e}}^0 : F_x^0 = 1 : 1 : 1$, which is one reference value we will use in our analysis. According to recent detailed studies of microprocesses taking place in supernova core, the flux ratios may considerably differ from this simple assumption. From the results of [20] we obtain, after integrating over the energy spectrum, the ratios $F_e^0 : F_{\bar{e}}^0 : F_x^0 = 4 : 3 : 2$, which we will use in the following.

Let us first assume that no active-sterile matter conversion takes place in the outer skirts of the star. The opposite case will be considered in the end of this chapter. We compute the flux ratios F_e/F_a , $F_{\bar{e}}/F_a$, and $F_{\bar{e}}/F_e$, where F_a is the sum of the fluxes of active neutrinos other than ν_e and $\bar{\nu}_e$. The results are shown in tables 1 and 2. In table 1 we have compared the values of relative fluxes with and without active-sterile vacuum mixing, for the normal and inverted mass hierarchy and for an adiabatic and non-adiabatic conversion at the high-resonance. We see immediately, that in the case of non-adiabatic transition in the high-resonance the ratios are independent of the mass hierarchy. This is in agreement with the conclusion of [15], that for $\sin^2 \theta_{13} < 10^{-6}$ the observation of supernova neutrinos are insensitive to the mass hierarchy. In adiabatic case, the relative amount of electron neutrinos is larger for the inverted hierarchy. The mixing with sterile neutrinos widens the range of the possible values of the flux ratios in all cases. With equal initial fluxes the situation is more simple, as shown in table 2, in the sense that the ratios are independent of the neutrino mass hierarchy and the adiabaticity of the MSW conversions. Also in this case the active-sterile mixings considerably widen the range

of the possible flux ratios.

		Normal hierarchy		Inverted hierarchy	
		active	active + sterile	active	active + sterile
adiab.	$\frac{F_e}{F_a}$	0.18	0.12 – 0.28	0.22 – 0.25	0.16 – 0.33
	$\frac{F_{\bar{e}}}{F_a}$	0.28 – 0.29	0.18 – 0.46	0.20	0.14 – 0.31
	$\frac{F_e}{F_{\bar{e}}}$	0.63 – 0.67	0.61 – 0.72	1.07 – 1.21	0.99 – 1.35
non-adiab.	$\frac{F_e}{F_a}$	0.24 – 0.27	0.17 – 0.33	0.24-0.27	0.17-0.33
	$\frac{F_{\bar{e}}}{F_a}$	0.30	0.20 – 0.47	0.30	0.20 – 0.47
	$\frac{F_e}{F_{\bar{e}}}$	0.77 – 0.92	0.69 – 1.10	0.77 – 0.92	0.69 – 1.10

Table 1: Results with initial flux ratios 4 : 3 : 2

In a summary, the effect of the active-sterile mixing is in general less striking for the supernova neutrinos than what we found in our previous study [1] it to be for the UHECR neutrinos. The relative flux of the electron antineutrino can, however, differ from its nonsterile value as much as 50 % if the active-sterile mixing angles φ_i for different degenerate pairs differ suitably from each other. The basic reason for this is that the electron neutrino and antineutrino end up to different mass states in the surface of the star, so that their fluxes are sensitive to different active-sterile mixing angles.

	active	active + sterile
$\frac{F_e}{F_a}$	0.25	0.17 – 0.38
$\frac{F_{\bar{e}}}{F_a}$	0.25	0.17 – 0.38
$\frac{F_e}{F_{\bar{e}}}$	1.00	1.00

Table 2: Results with initial flux ratios 1 : 1 : 1. These values are valid for both normal and inverted mass hierarchy and independently of adiabaticity.

So far we have assumed that the MSW conversions between the active and sterile states do not occur, in other words, the transitions between the mass states $\nu_i = \cos \varphi_i \hat{\nu}_i - \sin \varphi_i \nu_{si}$ and $\nu'_i = \sin \varphi_i \hat{\nu}_i + \cos \varphi_i \nu_{si}$ are non-adiabatic. The adiabaticity depends on the profile of the envelope at the resonance region, as well as on the mixing angles φ_i and the mass-squared difference $m_i^2 - m_i'^2$. In order to get a feeling of what may happen, we have studied, utilizing the analysis of ref. [21], a case of mixing of one degenerate active-sterile neutrino pair more

closely, and we have found that for $m_i^2 - m_i'^2 \lesssim 10^{-11} \text{eV}^2$ the transition is highly non-adiabatic for mixing angles up to about 35° and adiabatic only in the case of nearly maximal mixing. For larger mass-squared differences adiabaticity can be reached with smaller mixing angles. In general there will be a range in the parameter values, where the transition is partially adiabatic. Obviously, our analysis does not make full justice to the problem, but it does convince us that the sterile mixing of the sort we have been looking at may have detectable effects.

Let us now assume that these transitions are fully adiabatic and the transitions $\nu_i \rightarrow \nu_i'$ do take place. In the case the mixing angle φ_i is close to maximal this would not have any influence on the fluxes of the active neutrinos. In contrast, if the mixing angle φ_i is small, the transition would mean a conversion of a predominantly active neutrino state into a predominantly sterile state, which would diminish the observable flux of supernova neutrinos at the Earth. The mixing angle φ_i cannot be, however, arbitrarily small, since for very small angles the transition would not be adiabatic (unless the mass-squared difference is large). Large effects are anyway possible, and if the mixing angles of different degenerate pairs differ from each other, the flux ratios may change dramatically. This can be seen in Table 3, where the flux ratios are presented for the case of the normal mass hierarchy and assuming adiabatic $\nu_i \rightarrow \nu_i'$ transitions. The mixing angle φ_i is allowed to vary in the range $5^\circ - 45^\circ$. The relative flux of the electron neutrino can substantially decrease as a result of these conversions.

		Normal hierarchy	
		$F_e^0 : F_{\bar{e}}^0 : F_x^0 = 4 : 3 : 2$	$F_e^0 : F_{\bar{e}}^0 : F_x^0 = 1 : 1 : 1$
adiab.	$\frac{F_e}{F_a}$	0.004 – 0.21	0.005 – 0.24
	$\frac{F_{\bar{e}}}{F_a}$	0.30 – 0.64	0.26 – 0.49
	$\frac{F_e}{F_{\bar{e}}}$	0.006 – 0.64	0.009 – 0.97
non-adiab.	$\frac{F_e}{F_a}$	0.005 – 0.25	0.004 – 0.24
	$\frac{F_{\bar{e}}}{F_a}$	0.30 – 0.66	0.26 – 0.49
	$\frac{F_e}{F_{\bar{e}}}$	0.009 – 0.88	0.008 – 0.97

Table 3: Results with adiabatic $\nu_i \rightarrow \nu_i'$ -transitions

In considering the significance of the effects discussed above one should also consider the anticipated accuracy of the experimental determination of the supernova neutrino fluxes. For example, in the SNO detector, for a typical supernova in the Galaxy with a distance of 10 kpc, the relative uncertainty of the $\bar{\nu}_e$ and ν_a fluxes is about 5 % and that of the ν_e flux about 10 %

[22]. Consequently, the uncertainties of the determination of the flux ratios are roughly 5 % for $F_{\bar{e}}/F_a$ and roughly 10 %-15 % for F_e/F_a and $F_e/F_{\bar{e}}$. In the Super-Kamiokande detector the $\bar{\nu}_e$ flux can be determined more accurately, with the uncertainty of about 1 % (corresponding to about observed 10 000 events). The accuracy of the ν_a flux determination is estimated to be about 4 % (about 700 events) [22]. The ν_e flux is, in contrast, quite hard to determine at the Super-K. While noting that the effects of the active-sterile mixing we have discussed would be detectable in these detectors, we must stress the importance of developing methods of an accurate determination of the flux of electron neutrinos in future neutrino experiments.

5 Summary

We have investigated how supernova neutrino fluxes are affected by the existence of sterile neutrinos closely degenerate with active neutrinos. Sterile neutrinos are not produced in the core of a supernova, but in the matter eigenstates entering the surface of the supernova envelope sterile components are developed. We have used two sets of initial fluxes of neutrinos in the production region, $F_e^0 : F_{\bar{e}}^0 : F_x^0 = 1 : 1 : 1$, and $F_e^0 : F_{\bar{e}}^0 : F_x^0 = 4 : 3 : 2$. Matter effects were taken into account and we have explored both normal and inverted mass hierarchies. The effects caused by the degenerate sterile neutrinos will be detectable in future neutrino experiments. Particularly large effects are possible for the electron antineutrino flux.

It is possible, at least in principle, that the degenerate mass eigenstate pairs encounter a MSW resonance conversion in the outer skirts of the supernova envelope. This may dramatically change the relative fluxes of the neutrinos interacting in detectors. If the active-sterile mixing angles is small, a transition from a predominantly active state to a predominantly sterile state will occur, which can diminish e.g. the electron neutrino flux a lot.

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